Mars Planetary Network for Human Exploration Era – Potential Challenges and Solutions*

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During 2016-2017, a study was conducted under the sponsorship of the NASA's Space Communications and Navigation (SCaN) Program to investigate the deep space communications capacity taking into account the needs of all the present and envisioned future missions toward 2030s. It was soon recognized that planning for human exploration to Mars would impose certain unprecedent challenges, both fiscal and technical, to the current space communications paradigm. Targeting the assumed missions concepts, i.e., Crewed Mission to Phobos (CMTP) and Mars Short Stay Mission (MSSM), a Mars Planetary Network for the human exploration era has been formulated.

The activity modeling and network traffic simulation/modeling we performed gave some insight into the technical challenges in space communications for the envisioned human Mars exploration era. Chief among the potential challenges are: (1) the high demand on the deep space network (DSN) assets for achieving the high-rate links, both return and forward, from Mars farthest/farther distance (up to 2.67 AU); (2) the need for resilient, persistent communication coverage for crewed vehicles, on surface and in orbits; (3) the significant period of outage for the Mars-Earth link due to superior solar conjunction; (4) the need for on-demand, simultaneous access to the proximity link by multiple vehicles and astronauts in the exploration zone; (5) the capability of determining precise, real-time, positions of surface vehicles and astronauts by the deep space habitat and/or other teleoperations entities.

Solution space to each of the above challenges has been explored and analyzed in the context of the individual problem domain and, more importantly, in conjunction with that for the other challenges. This has led to an end-to-end definition of a Mars Planetary Network that would feature: (1) the fusion of deep space Ka-band and optical communications for achieving Mars-Earth high-rate links taking advantage of the optical/RF hybrid 8m/34m antennas in DSN; (2) the integrated application of the Multiple Spacecraft Per Antenna (MSPA) technique, for return link data acquisition, and the Multiple Uplink Per Antenna (MUPA) technique, for forward link data trasnmission, to reduce the number of 34m beam-wave guide (BWG) antennas needed for the era; (3) the integration of three, arrayed, 34m beam-wave guide (BWG) antennas, to provide a high G/T aperture, with the MSPA/MUPA techniques, and a dual "trunk link"approach to cut down the needed G/T -- hence, reducing the number of 34m antennas, relative to that in the single trunk approach by 50%; (4) the deployment of two areostationary/areosynchronous Mars relay orbiters; one of them could also function as (or be served by) a notional Deep Space Habitat (DSH); (5) the opportunistic deployment of a science orbiter in a Pioneer-6 type orbit, equidistant Mars/Earth, that could also serve as an intermediary relay during the Mars superior solar conjunction perod; (6) the existence of the multi-function Mars proximity link that provides the demand-assigned, multiple access (DAMA) capability; and (7) the provision of tracking observables, by leveraging on the planned Mars orbiting and surface infrastructure, to enable the in-situ navigation for surface and orbiting vehicles.

This paper provides the description of the proposed Mars Planetary Network in the human exploration era, the trade-off analysis for the various alternative architectures, and the optimal solutions to the key challenges in defining this end-to-end network.

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I. Introduction

In 2016, NASA's Space Communications and Navigation (SCaN) Office initiated, at the Jet Propulsion Laboratory (JPL), a "Deep Space Capacity Study" for the Interplanetary Network Directorate to investigate the Deep Space Network (DSN) communications capacity relative to projected future-mission demands over the next 30 years. It was soon discovered that, among all the different mission domains (including human Lunar exploration) supported by the DSN, human exploration to Mars would impose certain unprecedent challenges, fiscal and technical, to the current space communications paradigm. As shown in Figure 1, a notional timeline for the set of Mars missions between 2018 and 2040s, a series of precursor and crewed exploration missions would take place to prepare the way, e.g., in-situ oxygen and water production, for the Mars long stay mission. In addition, the deployment of key equipment to establish the long lasting communications infrastructure is a critical part of the overall human exploration program of this era. To assess the situation, specific human Mars exploration activities and their associated communications traffic were modeled. Of particular interest were two operations scenarios: the 24-day surface portion of the Mars Short Stay Mission and the surface portion of the Crewed Mission To Phobos. Activity modeling and network traffic simulation/modeling we performed gave some insight into the technical challenges in space communications for the envisioned human Mars exploration era. Analysis of the various communication links, i.e., direct-to-Earth, direct-from-Earth, and proximity links involving all the projected Mars orbiters, surface vehicles (exploration and science, crewed and robotic), and Earth stations (i.e., the DSN) led us to define a Mars Planetary Network with three viable architecture options.

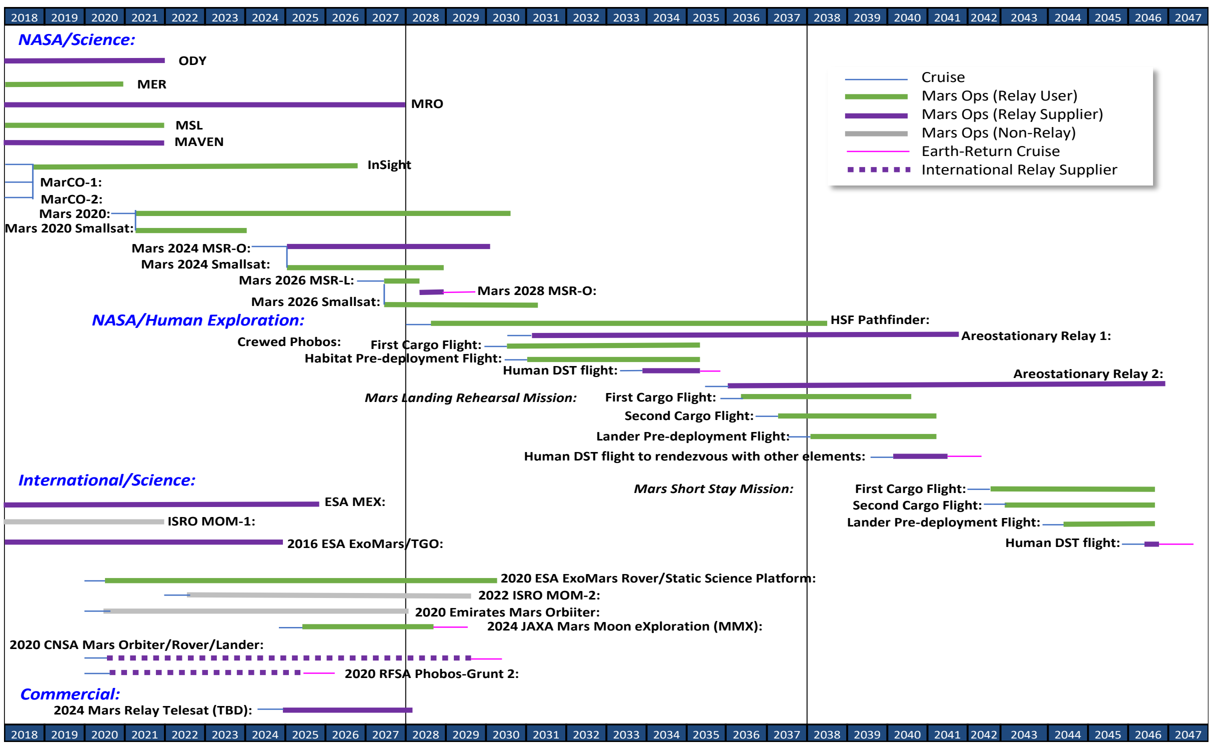

Figure 1. A Notional Timeline for Mars Missions Set (2018 – 2040s)

II. Challenges for a Mars Planetary Network

The Mars Planetary Network is defined as an end-to-end system that emcompasses the Mars relay network (i.e., one or more dedicated relay orbiters or relay payloads on hosting science/exploration orbiters) , Mars surface network (e.g., a wireless local area network at the exploration zone), and the Earth network (i.e., the DSN and the deep space stations of partner agencies). Collectively, they form the communications infrastructure to provide a set of standard services to all relevant Mars missions. A description of the Mars Planetary Network is covered in Section V.

For the human Mars exploration era, chief among the potential challenges for the Mars Planetary Network are:

(1) The high demand on the Deep Space Network (DSN) assets for achieving the high-rate links, both return and forward, from Mars farthest/farther distance (up to 2.67 AU) – Results of Mission Activity Modeling on both Mars Short Stay Mission (MSSM) and Crewed Mission to Phobos (CMTP) indicate a peak aggregate data rate of ~215 Mbps for downlink and ~28 Mbps for uplink over the Mars-Earth trunk line. While such data rates could easily be accommodated by the currently planned baseline capability of the DSN for periods of nominal Mars-Earth distance, for those weeks or even months of Mars farthest/farther distance, the demands would drive the DSN to dedicate a few more 34m BWG stations to support Mars missions alone.

(2) The resilient, persistent communication coverage for crewed vehicles, on surface and in orbits – Because of the energy constraints, Mars surface elements will seek to minimize direct-to-Earth (DTE)/direct-from-Earth (DFE) communications except when absolutely necessary. That means, surface elements will routinely resort to communicate via available relays. Hence, the Mars Planetary Network must provide *continuous, high-bandwidth* communications to human exploration zone. Longitudinal offset that allows continuous Earth connectivity is also important to the crew, in particular for longer stay missions. Since surface element critical to astronaut safety must transmit their mission-critical data back to Earth via at least two paths, such that a single point failure along one path (other than at the source) will not preclude receipt of the data, redundant communication paths for reliability must be a built-in feature of the Mars Planetary Network.

(3) The significant period of outage for the Mars-Earth link due to superior solar conjunction - During the period of Mars superior solar conjunctions, the effects of solar charged particles are expected to corrupt the data signals to varying degrees from degraded link performance to complete outages of communications. The period and state of outage are more severe in optical, lasting for 10 to 15 weeks, than in RF communications, lasting for a few days for X-band and much shorter for Ka-band. For Mars science and robotic missions, the flight mission control typically would scale down or suspend operations by executing certain special operational procedure, reducing tracking contacts, placing spacecraft in a safing mode, and progressively lowering data rates. For crewed Mars missions, however, the period of communication outage is extremely undesirable as it poses uncertainties, threats, and even risks to astronaut safety. Mitigation measures at affordable costs, therefore, becomes an integral part of the Mars Planetary Network architecture.

(4) The need for on-demand, simultaneous access to the proximity link by multiple vehicles and astronauts in the exploration zone – It is expected that much of the operational activities conducted for the MSSM and CMTP will be non-determistic in nature. Multiple surface elements will need access to the proximity link simultaneously. As the surface activities are being conducted step by step, in-situ measurement data will be acquired, collected, and returned accordingly. The relay orbiters, e.g., the Deep Space Habitat (DSH), must allow for automated, more efficient, and more easily available communications services, providing user vehicles with increased network performance supportive of dynamic and autonomous mission scenarios.

(5) The capability of determining precise positions of surface vehicles and astronauts by the Deep Space Habitat and/or other teleoperations entity in real-time - In addition to communication services, the human Mars exploration also requires the Mars Planetary Network to provide the capability of determining precise positions of surface vehicles and astronauts. Location awareness is essential to supporting various crewed and robotic activities on the Mars surface and on orbits. This includes localizing discoveries and returning to sites, construction and assembly of structures and habitats, entry/descent/landing, approach/rendezvous/docking, Mars ascent, and orbit insertion, etc.

III. Human Mars Exploration Activity Modeling

In order to ascertain the telecommunications requirements for a Mars Planetary Network in the human Mars exploration era, it is necessary to first understand what a representative set of human exploration activities might be, what communicating elements might be involved in each of those activities, which of the elements might actually be communicating with each other during each activity, and what the necessary data rates might be for each of those communications. This section summarizes the methodology and findings associated with pursuing this understanding with respect to the Mars Short Stay Mission and the Crewed Mission to Phobos.

A. Mars Short Stay Mission

In 2015, a "Humans-to-Mars Minimal Architecture" derivative of NASA's *Human Exploration of Mars Design Reference Architecture 5* emerged that identified certain key building blocks for sending humans to Mars (launch capability, in-space propulsion, crew quarters, surface elements, etc.) and worked out a minimal sequence of launches and associated timelines for various Mars missions.[1] In Pass-1 of the Deep Space Capacity Study, we focused on the first mission to the surface of Mars, the Mars Short Stay Mission (MSSM). In this mission concept, six SLS launches are used to enable a crew of four to get to Mars, with two of the crew then traversing down to the planet's surface for a 24-day stay.

We concentrated on identifying and characterizing the activities for three scenarios associated with the surface exploration portion of the mission. The first scenario, "Rendezvous, Crew Transfer, and Landing," began with a rendezvous between the Deep Space Habitat (DSH) used to transport the astronauts to Mars and a pre-deployed Lander. The next activity in this scenario involved crew transfer from the DSH to the Lander. The third activity involved Lander descent to low Mars Orbit, and the final activity involved Lander descent to the Mars surface. The second scenario, "Surface Ops," involved nine sequential activities: astronaut traverse via rover to a pre-deployed Cargo Test Lander, retrieval of an experimental oxygen production system and setup at its operational location, astronaut return to the pre-deployed cargo lander, retrieval and setup of an experimental drilling and water processing unit, astronaut return to their lander, astronaut preparations within the Lander, next-day astronaut traverse back to the drilling/water processing unit, astronaut conduct of drilling operations and water sample analysis, and return of the astronauts to their lander. The third scenario, "Ascent Day," entailed five activities: Mars Ascent Vehicle (MAV) pre-check for ascent, rendezvous with a MAV boost stage in low Mars orbit, MAV ascent via the boost stage to high Mars orbit, MAV rendezvous with the DSH, and crew transfer from the MAV to the DSH.

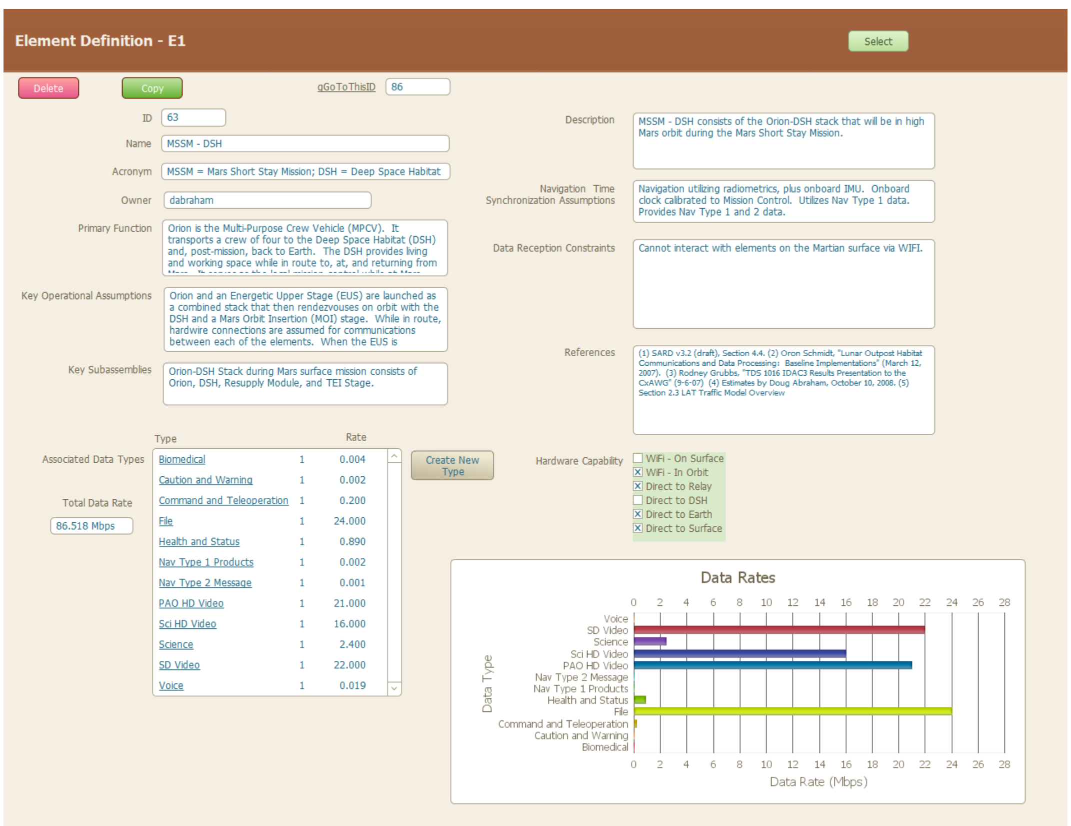

Figure 2. Example Characterization of a Communicating Element.

For each of the activities in each of the scenarios, we identified and characterized each communicating element and the data types and rates associated with it (exemplified in Figure 2). Across all of the scenarios, the MSSM elements active during the Mars surface mission included: Orion, DSH, MAV Boost Stage, DSH Resupply Module, Mars Orbit Insertion Stage, Lander, Crew Mobility Chasis, Oxygen Production System, Water Processing System, Rover, Portable Utility Pallet, the pre-deployed Cargo Test Lander, and the EVA suits. Non-MSSM elements assumed to be operating concurrently in the Mars environment included the un-crewed Mars EDL Test MAV, Mars Areostationary Relay 1, Mars Areostationary Relay 2, a Phobos Transfer Stage from an earlier crewed mission to Phobos, a Phobos Surface Habitat, and Phobos SEP Tug 1.

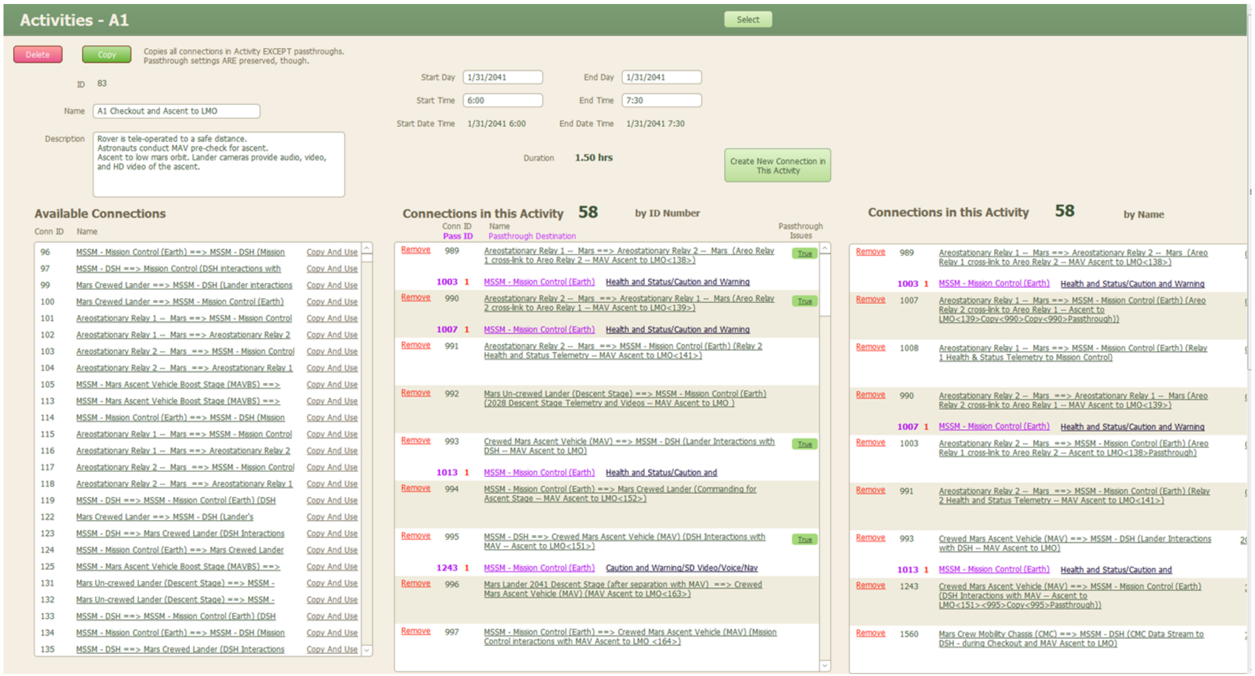

Figure 3. Example Specifications of Transmission from a Source Elements to a Destination Elements

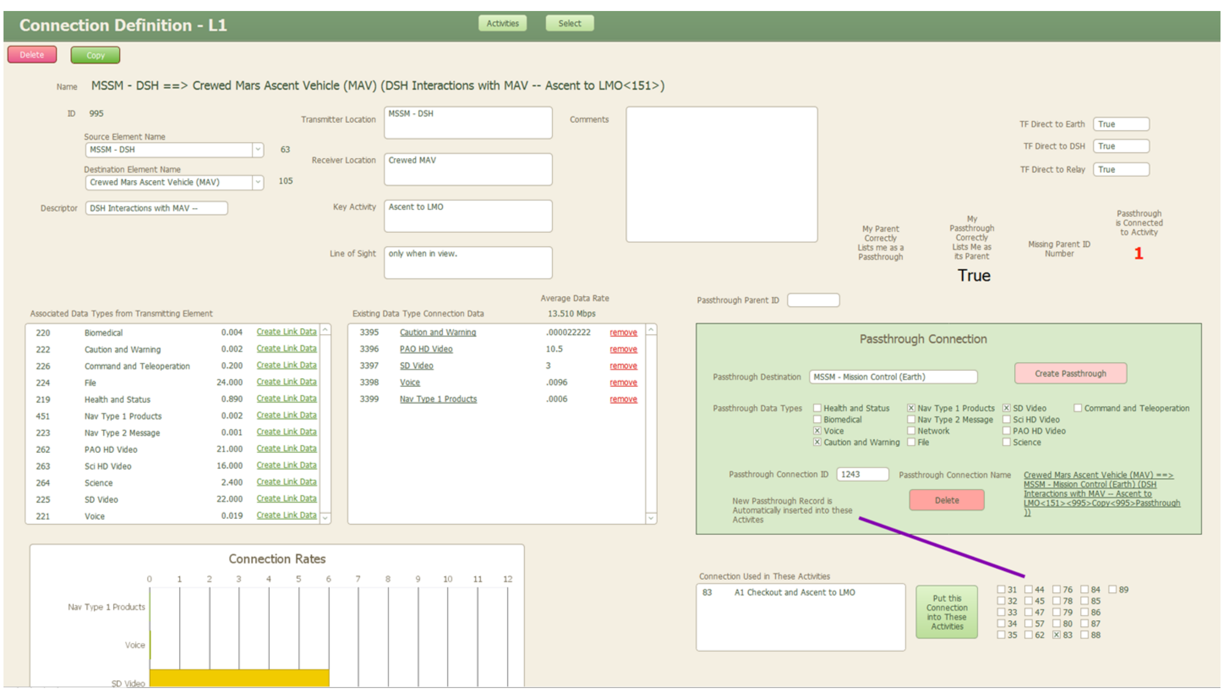

Figure 4. Example Specification of the Data Types and Rates within a Particular Transmission from a Source Element to a Destination Element

After characterizing each of the communicating elements, we then enumerated all of the communications connections occurring between elements within a given activity. Each communications connection consisted of a transmission from a source element to a destination element (as exemplified in Figure 3). We did not, at this point, attempt to define the physical pathway between the source and destination elements (which was done later in the network traffic modeling). We only focused on identifying all of the source-destination pairings, the data types, rates, and duty cycles associated with the transmission in each pairing, as well as certain parameters needed to inform subsequent network traffic modeling such as the acceptable latencies, redundancy requirements, and security requirements on each data stream (Figure 4). We did this for all of the activities in each of the scenarios considered.

Once all of the source-destination connections were specified for each of the activities comprising each of the scenarios, the associated data were then exported to tools that, in conjunction with models of the possible physical communication pathways, simulated the network traffic flows (discussed in the next section). As a first-order check on these network traffic simulations, aggregate maximum average data rates to Earth, from Earth, between the Mars relay elements and the Mars surface, and from a variety of other perspectives were computed directly from the data. The peak average aggregate data rate from Earth to Mars was ~28 Mbps. The corresponding data rate from Earth through a particular Areostationary Relay was ~15 Mbps. The peak average aggregate data rate from Mars to Earth was ~212 Mbps, with the corresponding rate through a particular relay being ~155 Mbps. For traffic both from and to Earth, video for public outreach, situational awareness, etc. was the single largest driver. Traffic from Earth through an Areostationary Relay tended to be less than what was predicted for analogous traffic in past lunar activity models because of the constraints that two-way light time impose on real-time interactions with Mission Control. Note that these results also assume nominal operations. Given the time and resource constraints associated with the study, the modeling of emergency scenarios such as mission element failures and crew-related medical emergencies were left as future avenues of investigation -- avenues that could potentially have a bearing on aggregate rate requirements or necessitate adopting special procedures to live within the nominal level of communications capacity.

B. Crewed Mission to Phobos

For Pass-2 of the Deep Space Capacity Study, the sponsor expressed interest in understanding the network traffic implications of the postulated predecessor to the Mars Short Stay Mission: the Crewed Mission to Phobos. In this humans-to-Mars minimal architecture mission concept, four SLS launches are used to enable a crew of four to get to Mars and then traverse down to a pre-deployed habitat on the surface of Phobos where they spend roughly 300 days before returning to Earth.[2]

We concentrated on identifying and characterizing the activities for five scenarios associated with the Phobos surface exploration portion of the mission. Activity and scenario development drew upon extensive Phobos exploration planning by Astronaut Gernhardt and his team at Johnson Space Center.[3] The first scenario, “Departure to and Arrival at Phobos Habitat,” began with a rendezvous between the Deep Space Habitat (DSH) used to transport the astronauts to Mars and a pre-deployed Phobos “Taxi.” The next activity in this scenario involved crew transfer from the DSH to the Phobos Taxi. The third activity involved transit of the Phobos Taxi to the Phobos Habitat. The fourth activity involved crew transfer to the Phobos Habitat, and the final activity involved Habitat system activation and checkout. The second scenario, “Venturing Out of the Habitat,” involved four sequential activities: performing a 1.5-hour pre-breathe and egressing the airlock, deploying outrigger booms and performing surface sample collections, checking out Manned Maneuvering Unit (MMU) systems and evaluating via tethered flight, and returning to and ingress of the Habitat. The third scenario, “Exercising the Pressurized Excursion Vehicle (PEV),” also began with performing a 1.5-hour pre-breathe and egressing the airlock, followed by transiting to the docked PEV and ingress through the suit ports. Additional activities included: checking out the PEV systems and beginning an evaluation of the PEV’s flight performance in the Phobos environment, assessing EVA methods including work via the MMU while tethered to the PEV outriggers, and performing a contingency walk back to the Habitat with one astronaut while the other follows in the PEV. The fourth scenario involved Low-Latency Teleoperations (LLT) from the Phobos Habitat. These teleoperations activities focused on ISRU-related elements on the surface of Mars and were derived from the low-latency teleoperations analyses performed by the Human Spaceflight Architecture Team (HAT) as part of the Evolvable Mars Campaign.[4] Activities included: performing an ISRU site survey, conducting habitat maintenance when out of view, sampling prospective drilling sites and performing vibro-acoustic testing while in view, auto-analyzing samples while out of view, conducting drilling operations while in view, and auto-analyzing core samples from drilling while out of view. The fifth and final scenario, “Habitat and Astronaut Maintenance,” began with resting, exercise, eating, and personal time. This was followed by tending to Habitat maintenance activities, science experiments, and remote science observations. Finally, the scenario concluded with sleep time and personal hygiene, with all crew members assumed to follow the same sleep schedule.

As with the Mars Short Stay Mission, we began modeling all of these scenarios and their associated activities by identifying and characterizing all of the communicating elements, their data types, and associated data rates. Crewed Mission to Phobos (CMTP) elements active during the Phobos surface mission included: Orion, the Deep Space Habitat used to transit to Mars, the Phobos Taxi, the Mars Orbit Insertion Stage, the PEV, EVA Suits, MMUs, a Mars Deep Drill Rover (on the Mars surface for teleoperations), and three Mars Microdrop Carrier Payloads to be used during teleoperations for site survey, sample collection and analysis, and drilling observation. Non-CMTP payloads included a couple of smallsat orbiters, smallsat landers, and Phobos Hedgehogs.

After characterizing each of the communicating elements in the same manner as was done for the Mars Short Stay Mission, we then enumerated all of the communications connections occurring between elements within each activity. As before, the associated data were then exported to tools that, in conjunction with models of the possible physical communication pathways, simulated the network traffic flows (discussed in the next section). And, a first-order check on these network traffic simulations was conducted by computing maximum average data rates between Earth and Mars for each of the activities. Table 1 summarizes the minimum and maximum cases for the Crewed Mission to Phobos and compares them with the corresponding values for the Mars Short Stay Mission. The two missions appear to have comparable average data rate requirements. As noted earlier, these data rate requirements only apply to nominal operations. Mission failures or crew-related medical emergencies could potentially have a bearing on aggregate rate requirements or necessitate adopting special procedures to live within the nominal level of communications capacity.

Table 1. Crewed Mission to Phobos Minimum and Maximum Average Data Rates Relative to Those for the Mars Short Stay Mission

Mission	Earth-to-Mars (Min)	Mars-to-Earth (Min)	Earth-to-Mars (Max)	Mars-to-Earth (Max)
Crewed Mission To Phobos (CMTP)	1.7 Mbps	111.7 Mbps	24.7 Mbps	200.8 Mbps
Mars Short Stay Mission (MSSM)	11.6 Mbps	93.7 Mbps	28.4 Mbps	211.9 Mbps

IV. Network Traffic Modeling for the Mars Short-Stay Mission

We consider three operation scenarios of the 21-day Mars Short Stay Mission as discussed in the previous section. We use the detailed mission activities discussed in previous section as input, as well as the latency requirements of different data types to drive the end-to-end data flow. We then use a 2-state Markov scheme as discussed in two earlier papers[5,6] to model the store-and-forward mechanism of each network node to simulate the onboard storage and link capacity profiles. We generate multiple independent and identically distributed observations (~300) using different initial conditions to obtain upper and lower bounds and statistical characterizations of important design parameters, e.g. bandwidths, onboard storage, etc.

The notional Mars relay network includes three orbiters: two areostationary orbiters, where at least one is continuously visible from the Mars landing site, and the Deep Space Habitat (DSH) in a 48-hour elliptical orbit. The three orbiters are in view of one another most of the time, and they can transfer data among each other via S- and Ku-band cross-links. The orbiters form a “network in the sky”, providing X- and Ka-band communications and tracking services as well as supporting DTN, data store and forward services, data backup, data re-transmission, data purging, and off-nominal data routing functions to surface assets in the vicinity of the Mars landing site and the low Mars orbiting spacecraft. This concept-of-operation (CONOPS) is shown in Figure 5.

We assume that the Mars landing site is equipped with a Wi-Fi hotspot that collects and distributes data between the Mars surface elements and the orbiters. We assume all Mars proximity links are RF. For orbiters direct-to-Earth (DTE) and direct-from-Earth (DFE) links, we consider two cases: a) RF only, and b) RF + Optical.

The network traffic model generates user count, data rate, and onboard storage timelines/statistics to support relay orbiter DTE/DFE and proximity link communication system design. This includes:

1. Sizing relay orbiter onboard storage requirements.
2. Allocating different data types to different simultaneous bands (X, Ka, optical, etc.) of a link based on data criticality and latency requirements.
3. Sizing the relay orbiter DTE/DFE links (RF and Optical).
4. Sizing the number of simultaneous proximity link users for multiple access (MA) and phase array design.
5. Sizing the relay orbiter proximity links (single-access (SA) and MA).

An example of the DSH DTE link timeline and statistics is shown in Figure 6.

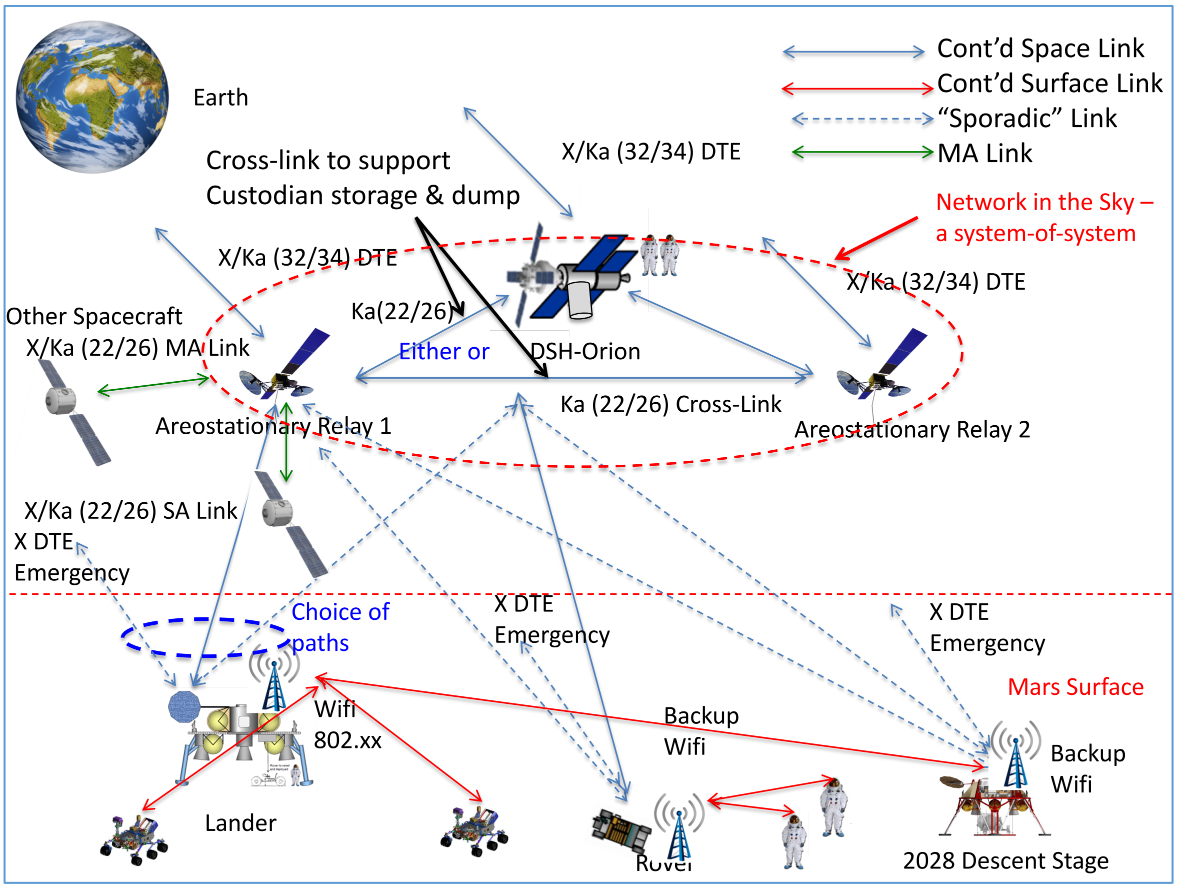

Figure 5. CONOPS of Mars Short-Stay Mission

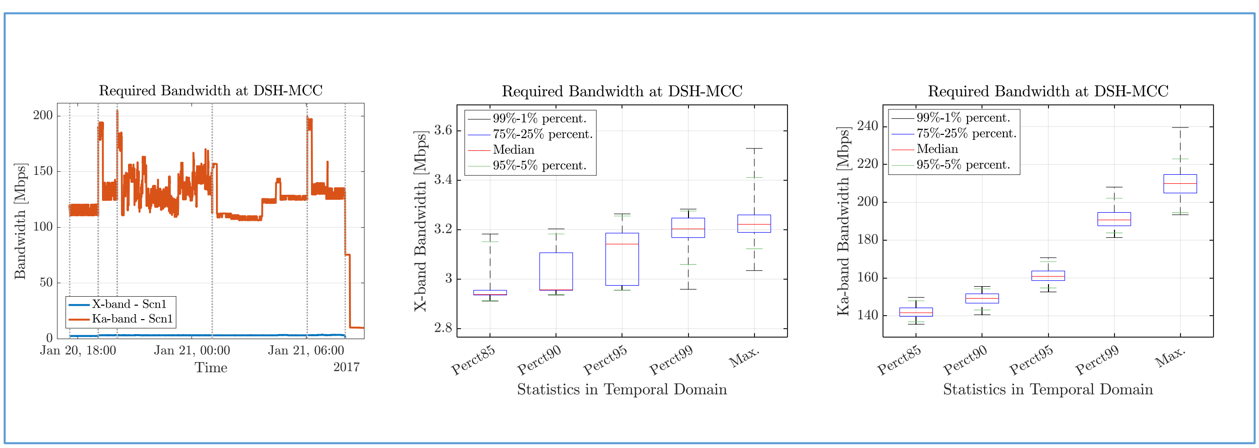

Figure 6: Example of DSH DTE link Timeline and Statistics

Based on the CONOPS and the network traffic modeling and simulations, we generated the following recommendations on the Mars relay orbiter design:

1. One parabolic antenna for DTE/DFE links, using deep space X- and Ka-bands.
2. One optical communication telescope for DTE link (RF + Optical case only)
3. One steerable parabolic antenna for cross-link, using near-Earth Ka-band.
4. One steerable parabolic antenna for proximity SA link, using near-Earth X- and Ka-bands.
5. One phase array system with onboard beamforming for MA links, using near-Earth X and Ka band to support 4 – 10 simultaneous users.
6. 200+ GB for store-and-forward, and 1000+ GB for custodian storage and dump operations.

For link sizing, we consider the median of the 95-percentile bandwidth in all subsequent discussion. For the RF-only case, the maximum bandwidths and number of users are summarized in Table 2:

Table 2: Maximum 95-Percentile Data Rate and Number of Users for RF-only Case

	Max. Forward Link (DFE) Data Rate	Max. Return Link (DTE) Data Rate
Orbiter-Earth Link (X-Band)	0.2 Mbps	6.1 Mbps
Orbiter-Earth Link (Ka-Band)	28 Mbps	255 Mbps
Orbiter-Mars SA Prox. Link (Ka-Band)	66 Mbps	355 Mbps
Orbiter-Mars MA Prox. Link (Ka-Band)	27 Mbps	59 Mbps
Number of Simultaneous Users	5	6

For the RF + optical case, adding the optical links impact the orbiters' DFE and DTE links only. The results are summarized in Table 3:

Table 3: Maximum 95-Percentile Data Rate and Number of Users for RF + Optical Case

	Max. Forward Link (DFE) Data Rate	Max. Return Link (DTE) Data Rate
Orbiter-Earth Link (X-Band)	0.2 Mbps	6.1 Mbps
Orbiter-Earth Link (Ka-band)	9 Mbps	94 Mbps
Orbiter-Earth Optical Link	21 Mbps	202 Mbps

Comparing Table 2 and Table 3, optical links greatly relieves the burden of RF links, both for the DFE and DTE links, thus requiring fewer 34-m BWG antennas dedicated to support the Human Mars Missions.

We observed many data rate spikes on the forward links, both for DFE and proximity SA links. These spikes create a jump at or beyond the 95-percentile value. Upon careful examinations we found that these spikes consist of time-critical software patch files, thus cannot be ignored indiscriminately.

V. Mars Planetary Network Architecture

As depicted in Figure 7, the Mars Planetary Network is an end-to-end system that emcompasses the Mars relay network, Mars surface network, and Earth network. The Mars relay network is comprised of one or more dedicated relay orbiters and any relay payloads on the hosting science/exploration orbiters. A Mars surface network is esentially a wireless local area network that connects all communication devices to support inter-vehicle and astronaut communications at the exploration zone. The Earth network includes the NASA's DSN and the deep space ground stations of NASA's partner agencies who are involved in the Mars exploration. Collectively, they form the communications infrastructure to provide a set of standard services to all participating Mars missions. As a service-providing network in this era, its communication capabilities exist at physical, data link, and network layers. Unlike the current form of the Mars Network, it is an interplanetary space internet that employs the standard DTN internet protocol. We call it the Mars Interplanetary Space Internet analogous to the terrestrial Internet that has been in place for more than three decades. Like the internet, the three networks are interconnected. Like the internet, there exists a space internet protocol, the Disruption Tolerant Network (DTN) protocol,[8] and, as shown in Figure 7, each major element of the Mars Planetary Network is a DTN node.

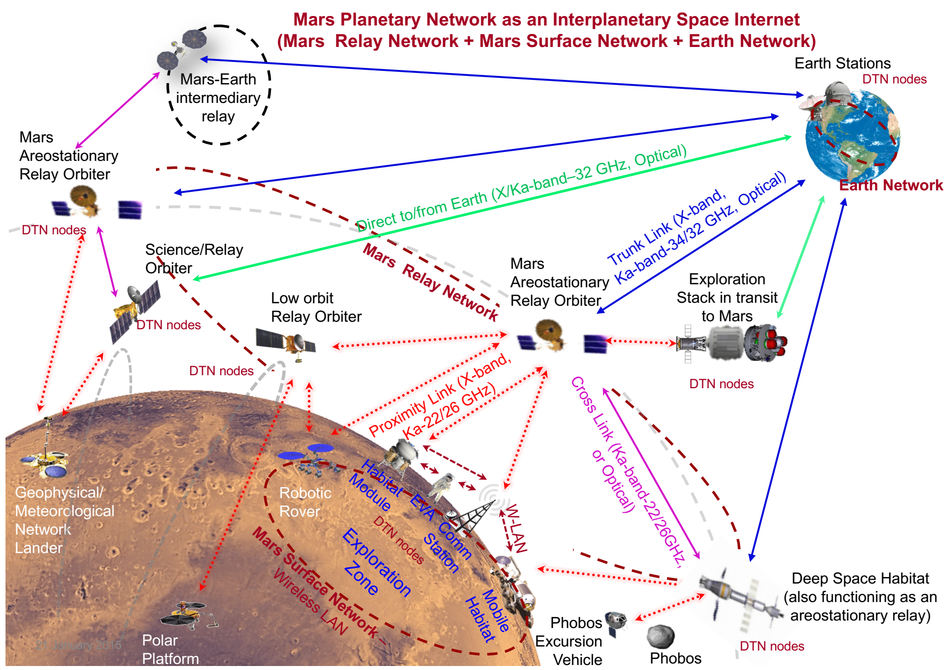

Figure 7. Mars Planetary Network – Top Level View

The features of the Mars Planetary Network were selected based on certain solutions we considered for meeting the communication challenges as enumerated in Section II, some of which further quantified in Sections III through IV.

Specific to Challenge #2, i.e., the resilient, persistent communication coverage for crewed vehicles, on surface and in orbits, an obvious solution lies in the relay capabilities provided by two areostationary relay orbiters, at much higher altitude than the typical Mars science orbiters, and the Deep Space Habitat (DSH) may also function as one of them. The areostationary orbit characterized by 17,300 Km altitude (or lower) in a circular, equatorial orbit would offer continuous view of an exploration zone (>10-degree elevation), with global coverage to areas within +/- 70-degree latitude. Moreover, by their geometry the relay orbiters would be able to maintain continuous contact with the DSN, a feature critical to Challenge #1 as well. While a single relay spacecraft at this orbit would be sufficient to fulfill the coverage and link requirements with respect to an exploration zone, two are needed to ensure service reliability and resilience. This is consistent with the assumption made in most, if not all, NASA-internal human Mars exploration studies.

Spacecraft bus of the relay orbiter would have to be a commercially available, moderate size, satellite, with full redundancy. Spacecraft mass is estimated to be ~1500 kg at launch, 1200 kg dry mass and 300 kg for propellants. The two relay orbiters are identical, will be launched via separate launch vehicles or co-launched via the same launch vehicle, and will fly to Mars separately using solar electric propulsion (SEP). The spacecraft will be powered by ~20–30 kW solar arrays.

The resilient, persistent communication coverage also demands the areostationary orbiter be equipped with high-performance directional terminal/antenna to communicate with user vehicles via X-/Ka-band and/or optical links. The departure from the UHF band imposes a need for active pointing at both ends of the proximity link. To provide relay support to orbital user vehicles, in addition to those on Mars surface, higher slew rates of the proximity link antenna and the ability of the relay orbiter to compensate for their high Doppler rates are essential for achieving 4π sr proximity link antenna pointing.

Solutions to Challenge #4, i.e., the need for on-demand, simultaneous access to the proximity link by multiple vehicles and astronauts in the exploration zone, involve a combination of new capabilities at the physical and data link layers. Regarding on-demand access to proximity link, the emerging Unified Space Link Protocol (USLP)[7] defined by the CCSDS should be a good choice. Unlike the current Proximity-1 Protocol, which was designed for link data rates below 2 Mbps, the USLP is capable of operating in high-rate environment. The USLP has inherited the Proximity-1 hailing and working channel mechanisms to allow on-demand access to the link. And to address the need for smultaneous access by multiple user vehicles, we have derived a solution as follows:

(1) The frequency bands we selected for Mars proximity link are near-Earth X-/Ka-band (and Ka-band for crosslink), as shown on Figure 7.
(2) The relay orbiter will carry a phased array antenna with beamforming capability to allow simultaneous multiple access by users. The phased array antenna is amenable to X-/Ka-band, but not UHF-band. This is because of the mass of the phased array system; scales with wavelength to the power of 1.5, and to the power of 2 to compensate for the frequency ratio.
(3) Phased array allows beamforming that can track multiple spacecraft that are far apart within some maximum scan angle (for the Ka-band phased array reference design in the industry study, it is 13 degree). This is important for relay coverage of multiple user vehicles on surface and in orbit.
(4) The FDMA/TDMA/CDMA scheme are not chosen (TBC) since, when the HGA is used, the beamwidth is small, so it might not be very useful except for a small local region, e.g. Mars landing site.

Solutions to Challenge #3, i.e., the significant period of outage for the Mars-Earth link due to superior solar conjunction: An obvious solution to this challenge is the deployment of an intermediate relay satellite near Sun-Mars/Sun-Earth L4/L5 orbit or a Pioneer 6-like orbit. The long range from Mars to any stable locations in these orbits is a challenge. It would make the link between Mars to the intermediate relay feasible only at very modest data rate, e.g., on the order of ~100 Kbps. Even for meeting this kind of data rate, the Mars-relay link would require a 6m antenna on both point, with 150 -175 W transmitting power. Results from recent study at JPL showed certain improved solutions.[9] They will be presented at this SpaceOps conference.

Any solution to Challenge #5, i.e., the capability of determining, in realtime, precise positions of surface vehicles and astronauts by the deep space habitat or other teleoperations entity, would undoubtedly calls for existence of a GPS-like infrastructure that would cover the vicinity of the entire exploration zone.

A general method that makes use of the proposed Mars relay network infrastructure, and a number of notional Mars orbiting and surface missions in the human Mars era, is being studied jointly by Georgia Tech and JPL.[10] It assumes two areostationary Mars relay orbiters that have continuous line-of-sight visibility with the Mars landing site, a Deep Space Habitat (DSH), and a surface communication lander that can serve as the reference point. These orbiting and surface vehicles would broadcast GPS-like ranging signals and other ephemeris information to the user vehicles. With one or more additional orbiters in areosynchronous orbits that trace around a figure-8 path, a regional navigation satellite system can be realized that provides in-situ course absolute localization, precision relative localization, and timing services to the users in the vicinity of the Mars landing site. A variation of this approach that requires fewer orbiting vehicles will also be analyzed by the joint team. In this variation, two relay orbits in an orbit lower than areostationary, will have relative motion with respect to a surface vehicle. So when a surface vehicle is stationary and is in view with the two relay orbits, one can compute the location of the surface vehicle from the change in geometry. This would require good orbit solutions for the orbiters from the DSN periodically.

Perhaps, Challenge #1, i.e., the high demand on DSN assets for achieving the high-rate links, both return and forward, from Mars farthest/farther distance, is the most daunting of all. Mission Activity Modeling on both Mars Short Stay Mission (MSSM) and Crewed Mission to Phobos (CMTP) indicated a peak aggregate data rate of ~215 Mbps for downlink and ~28 Mbps for uplink over the Mars-Earth trunk line. Taking into account certain margin for future growth, in this study we decided to size the maximum demand on DSN capacity to ~250 Mbps and ~30 Mbps, respectively. At maximum Mars-to-Earth range (~2.67 AU) using 32 GHz Ka-band link, given the spacecraft telecommunications design based on a 6m deployable high gain antenna, a 420-500W transmitter, QPSK modulation, and an LDPC rate ½ forward error correction code, an array of six 34m antennas at each DSN site will be needed to close the downlink at any given time. In order to support Mars missions alone, in the human Mars exploration era, it would require eighteen dedicated 34m antennas. Needless to say, this would be a huge cost burden to NASA. To mitigate the demand and burden on the DSN, we had to pursue more cost-effective solutions. Since optical communications tends to require less mass and power than RF communications while achieving very high data rates, we assessed a variety of RF and optical approaches.

A. The Concept of Mars Relay Dual-Trunk Link with Earth

The concept of Mars Relay Dual-Trunk Link to Earth for downlink is predicated upon the existence of a relay-to-relay crosslink with an associated operational scenario at Mars vicinity as follows:

(1) The user vehicles on Mars surface and in orbit transmit their data to one of the two areostationary relay orbiters via the 26 GHz Ka-band for the high-rate proximity link. Two cases are assumed: (a) two relay orbiters are set up in a prime-backup relation and only the prime is in communications with all user vehicles; (b) each relay orbiter can be in communications with certain number of user vehicles. However, at any given time a user vehicle can communicate with only one of the relay orbiters.

(2) The two relay orbiters maintain a persistent or periodic, regular crosslink between them using the 22/26 GHz Ka-bands. Through a load-balancing algorithm, the data stored at the two relay orbiters are kept at approximately equal volumes, i.e., in a synchronized fashion. For ease of ensuring data integrity at the DSN, the data exchanged between the user vehicls, the two relay orbiters, and the Earth network must be at some suitable granularity of identifiable data set, e.g., in DTN bundles or file.

(3) As (1) and (2) are taking place, the two relay orbiters can also maintain their respective DTE/DFE links, using the 32/34 GHz Ka-bands, with the same DSN site, and simultaneously downlink the data sets stored on-board.

Therefore, the total data volumes acquired by the Mars relay are split between each of the relay orbiters, such that they would each downlink half their data at half the maximum data rate, i.e., at 125 Mbps, during the peak aggregate data periods. The benefit of the dual-trunk link architecture is that in comparison to the single-trunk link approach it cuts down the required number of DSN 34m antennas by half, i.e., three instead of six at each DSN site and nine instead of eighteen throughout the DSN. Such aperture and G/T advantages would be achieved by two special DSN configurations, i.e., the antenna arraying and multiple spacecraft per antenna (MSPA). Another special configuration that would supplement the dual-trunk link approach, although in a lesser role in the architecture, is the multiple uplink per antenna (MUPA).

For downlink at 125 Mbps, an arraying configuration with three DSN 34m antennas would provide sufficient G/T to close the link with a relay orbiter. At the same time, each of these same three 34m antennas, configured in MSPA mode, can acquire Ka-band signals, at two different frequencies, from both relay orbiters simultaneously. Our analysis indicates that the Ka-band MSPA is feasible because (a) both spacecraft would be within the same beam of the three arrayed antennas; (b) the longitudinal offset of the two areostationary orbiters that allows maximum Mars coverage by both, while within mutual visibility to Earth, could be up to ~160 degrees.

The concept of Dual-Trunk Link for high-rate uplink also relies an operational scenario, and protocol features, that involves the Mars relay-to-relay crosslink:

(1) Two of the three 34m antennas arrayed for high-rate downlink maintain their respective DFE 34 GHz ka-band links with the two relay orbiters.

(2) At the DSN, the upload received from the MOC for uplink is split into two uploads of approximately equal volume. For ease of ensuring data integrity at the destined relay orbiter, the data in each upload must be accounted for at the granularity of identifiable data sets, e.g., in DTN bundle or file.

(3) Each of the two 34m antennas radiates one of the two uploads designated to one of the two relay orbiters. The uplink rate for each is 15 Mbps yielding a combined uplink rate at 30 Mbps.

(4) The two relay orbiters maintain a persistent or periodic, regular crosslink using the 22/26 GHz Ka-bands.

(5) At the receiving ends, the areostationary orbiter designated as the backup would “continuously” forward the upload it received to the prime.

(6) Ultimately, the areostationary orbiter designated as the prime will manage to assemble the complete upload.

(7) As (3) through (6) are taking place, received data units, i.e., DTN bundles, are routed to the individual user vehicles.

In addition to these physical and data link considerations for achieving the required data rates, an important component is the adoption of the DTN protocols for the end-to-end transmission of data in the network. Instead of having to carefully plan and manage all of the data loading, store and forward capacities, data flows through multiple nodes, and end point data delivery, the DTN protocols manage all of this automatically. This enables the use of the Dual-Trunk configuration and maintains data integrity, DTN includes store and forward features, but it also supports delivery of streaming, high priority, voice and video data when requested. Because of the long OWLT many of these transfers may be handled as files, but in some cases the most timely delivery of data is called for. In addition to the use of DTN, the CCSDS File Delivery Protocol (CFDP) ensures reliable delivery of complete files.

B. Mars Dual-Trunk Link with Earth – DSN Architecture Options

Applying the concept of Mars Dual-Trunk Link with Earth to an option space (for high-rate link) involving both RF and optical communications, we have identified three alternative architectures for the DSN in the human Mars exploration era. These options, while they share many common features, are quite different in the aspect of high-rate downlink, hence they are designated as the RF-only, Optical-only, and Combined RF-Optical options. Figure 8 – 10 depict the three alternatives. The figures are much simplified as they omit the processing chains for uplink at DSN since one of the purposes of these figures is to illustrate the variations for high-rate downlink data acquisition and processing.

Common capabilities to all three options are the following:

(1) X-band uplink and downlink are a given. They are essential for engineering TT&C purposes. Relative to Ka-band and optical communications, they provide higher link availability, even if at lower rates.
(2) X-band downlink via MSPA: In each diagram, the string of dark blue-colored functions depicts the X-band downlink data streams from both relay orbiters and other Mars spacecraft would be acquired by a single 34m station and processed via the n-MSPA configuration (where n is the number of source spacecraft and would be extended to greater than the current 4). In the n-MSPA configuration, the X-band full-band processing capability allows the X-band downlink signals from all Mars spacecraft to be simultaneously acquired and telemetry frames from each Mars spacecraft to be generated using a separate receiver assigned to each source spacecraft.
(3) X-band uplink via MUPA: For a collection of Mars spacecraft that resides in close angular proximity to each other, as in the case of human Mars exploration, MUPA is feasible. Of all the approaches we assessed, the most practical one is based on a scheme where uploads for multiple spacecraft are multiplexed onto a single uplink frequency.[11] All spacecraft would lock onto the uplink signal and maintain two-way coherence with their respective downlink frequencies. Each would accept only the frames for its own upload data, differentiated by spacecraft ID. The spacecraft transponder would need the capability of sweeping and achieving lock (for uplink acquisition) in event of large differential Doppler shifts. For two-way coherent tracking variable turnaround ratios on the spacecraft transponder are required. That will require approval by the CCSDS for standardization. The MUPA study conducted at JPL has suggested that this approach would be easier to implement and operate. It would require some software changes in DSN to accommodate its uplink operation procedure and the two-way Doppler/ranging involving multiple spacecraft.
(4) Ka-band uplink is a given (even for Optical-only option). Earth-based Ka uplink offers significant cost advantages over optical uplink to Mars at its farthest distance from Earth. Optical uplink for deep space is at present a technical challenge – (a) <u>Earth telescope-based</u> optical uplink is not technically feasible because the atmosphere limits the beam width to certain minimum size, regardless of the ground aperture size. The atmospheric effects are just too severe. A brute force calculation showed that in order to uplink to a 50 cm aperture on the spacecraft side at 30 Mbps at Mars farthest distance, the laser transmit power required would be in the order of 260 W. This is a more a physical constraint. (b) <u>Earth-orbiting relay-based</u>: Unlike near-Earth laser communications, our analysis concluded that uplink to a 50 cm aperture on the Mars relay orbiter from an Earth-orbiting relay satellite would require the latter to be equipped with a 2m aperture using 250 W laser power in order to achieve 30 Mbps uplink rate. This is a big cost driver, although not a technological one.

(5) Ka-band uplink over the dual-trunk link: To achieve 30 Mbps uplink data rate by a single 34m antenna, the difficulty lies in the higher-power transmitter for 34 GHz Ka-band. Arraying two 34m antennas for uplink is certainly a good solution. The technique has been demonstrated and is no longer a technology issue. However, the same dual-trunk link approach used for the high-rate downlink process can also be applied to high-rate uplink, rendering antenna arraying for uplink unnecessary. In this scheme, exemplified by the RF-only option as illustrated in Figure 8, two of the three antennas used for downlink would each radiate forward data at 15 Mbps to a relay orbiter to achieve a combined data rate of 30 Mbps. The antenna should be able to close the link using a 1 kW 34 GHz transmitter which is not too much a cost driver. The dual-trunk link approach for uplink is a much cheaper solution than antenna uplink arraying because of the higher implementation cost and operational complexity of the latter.

(6) DSN Common Platform: By 2021, the system based on the DSN "common platform" design[12] will be deployed to fulfill the chains of downlink processing functions (see Figures 8, 9, and 10). Through the common platform, signals are digitized at the output of the down converters at the antennas and are distributed via a digital IF switch to the processing platforms. And a set of common hardware for signal processing applications, e.g., telemetry, tracking, radio science, and Very Long Baseline Interferometry (VLBI), are employed. The achievable maximum throughput for downlink acquisition processing at each chain of processing is 150 Mbps.

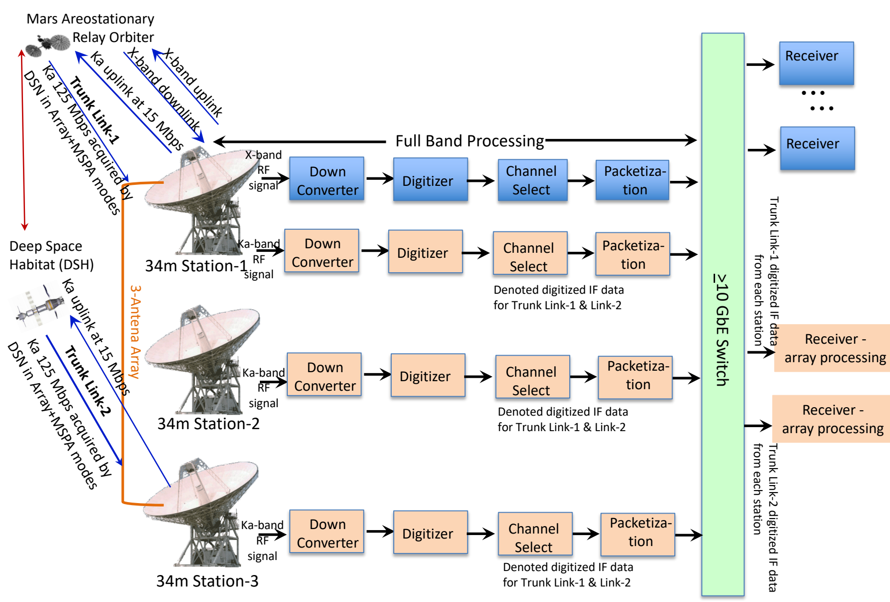

Figure 8. Mars Relay Dual-Trunk Link with Earth: RF-Only Option

RF-only option:

The architecture in the RF-only option is characterized by the use of 32 GHz Ka-band for the dual-trunk link established and maintained between the two Mars relay orbiters and an array of three 34m BWG antennas at a DSN site to accomplish the high-rate downlink acquisition and processing at persistent 250 Mbps rate. As discussed earlier, the dual-trunk link approach would allow the two halves of the trunk link (designated as Trunk Link-1 and Trunk Link-2 in the figure), each at 125 Mbps, to be acquired by a single three antenna array using a 2-MSPA configuration, in which each 34m antenna of the array is supporting both relay orbiters simultaneously. As shown by the three strings of orange-colored processing functions in Figure 8, at the DSN site, each 34m antenna would acquire the entire Ka-band (500 MHz) RF signal from both relay orbiters, down-convert the RF signal to IF and digitize the IF data, denote the digitized IF data streams into two different channels (one for each source orbiter). The digitized IF data, identifiable by two different channel IDs, would then be packetized for distribution to two receivers for array processing, i.e., IF signal combining, symbol detection, bit decoding, and frame synchronization and decoding. The output from each array processing receiver would be the frames from one of the two relay orbiters.

The amalgamation of this full-band processing capability of MSPA and signal combining for array processing is therefore a key feature of this architecture option. This MSPA/Arraying combo, along with the n-MSPA for X-band downlink, the MUPA for X-band uplink, and dual-trunk link for Ka-band high-rate uplink, would result in a much more efficient use of DSN assets to provide communication and tracking services to all Mars missions during the human exploration era.

Optical-only option:

The architecture in the Optical-only option is characterized by the optical dual-trunk link established and maintained between the two Mars relay orbiters and a single optical aperture currently planned for the DSN to accomplish the high-rate downlink acquisition and processing at a persistent 250 Mbps rate.

Figure 9 shows an architecture postulated for such an option. As proposed by JPL, the optical aperture would physically reside on a hybrid RF-optical antenna where an 8m-diameter optical aperture is placed near the sub-reflector of a 34m BWG antenna. Optical link calculation indicated that given a spacecraft optical terminal with 50 cm diameter aperture and 50 W laser transmit power, an 8m-diameter optical telescope would be able to achieve a downlink rate at 125 Mbps (for cases of maximum Mars-to-Earth range). In theory, the dual-trunk link approach would allow the two halves of the trunk link (designated as Trunk Link-1 and Trunk Link-2), each at 125 Mbps, to be acquired by a single 8m optical aperture using a 2-MSPA configuration at optical wavelength 1550 nm, in which the optical telescope is supporting both relay orbiters simultaneously. So, without adding additional ground aperture, the DSN would be able to get the 250 Mbps data-volume-equivalent down from both relay orbiters in a purely optical mode.

As depicted by the string of light-blue-colored processing functions in Figure 9, at the DSN site, a single 34m/8m RF-optical telescope would digitize the detected photons at the aperture, denote the digitized photon data streams into two different channels (one for each source orbiter). The digitized photon data, identifiable by two different channel IDs, would then be packetized for distribution to two receivers for typical telemetry processing, i.e., symbol detection, bit decoding, and frame synchronization and decoding. The output from each receiver would be the frames from one of the two relay orbiters. The 2-MSPA for photon acquisition and processing is therefore a key feature of the Optical-only architecture option. However, it must be noted here that the cost-effective method to handle the narrow beam-width associated with optical communications and the necessary frequency difference in the two trunk links is yet to be demonstrated.

Figure 9 also shows a single 34m antenna that would be dedicated to (a) X-band downlink using MSPA for supporting all Mars missions, (b) X-band uplink using MUPA for supporting all Mars missions in view, and (c) Ka-band uplink to one of the two relay orbiters. In that sense, this RF antenna is almost identical to that in the RF-only architecture. The only difference is it is not a part of the antenna array.

The RF aperture of hybrid RF-optical antenna would be used to radiate high-volume forward data at 15 Mbps. It, in operating simultaneously with the pure RF 34m antenna, would provide the necessary dual-trunk uplink capability.

This optical MSPA for dual-trunk downlink, along with the n-MSPA for X-band downlink, the MUPA for X-band uplink, and dual-trunk uplink for Ka-band high-rate, would result in a much more efficient use of DSN assets to provide communication and tracking services to all Mars during the human exploration era.

Combined RF-Optical Option:

The architecture in the Combined RF-Optical option is characterized by the combination of (a) an optical downlink established and maintained between one of the two Mars relay orbiters and a single optical aperture that would reside on the hybrid RF-optical antenna (as currently planned for the DSN), and (b) a 32 GHz Ka-band downlink between the other relay orbiter and an array of two 34m antennas and the RF portion of the hybrid RF-optical antenna, to perform high-rate downlink acquisition and processing at a persistent 250 Mbps rate.

As shown in Figure 10, unlike that in RF-only and Optical-only options, the dual-trunk link is not symmetric between the two halves. Unlike that in the Optical-only architecture, the optical aperture of the hybrid antenna would support an optical 125 Mbps downlink from only one of the Mars relay orbiters. There is no optical 2-MSPA configuration associated with the optical aperture in this option. Unlike that in the RF-only architecture, the antenna arraying is configurated using more heterogeneous assets, i.e., two 34m antennas and the RF portion of the hybrid RF-optical antenna, to support a 32 GHz Ka-band, 125 Mbps downlink from the other relay orbiter. The above dissimilarities would exhibit some interesting attributes of this architecture when compared to the other two (see Table 4).

For uplink, any two of the three antennas could transmit at 15 Mbps, each to one of the two areostationary relays, providing a combined uplink rate of 30 Mbps.

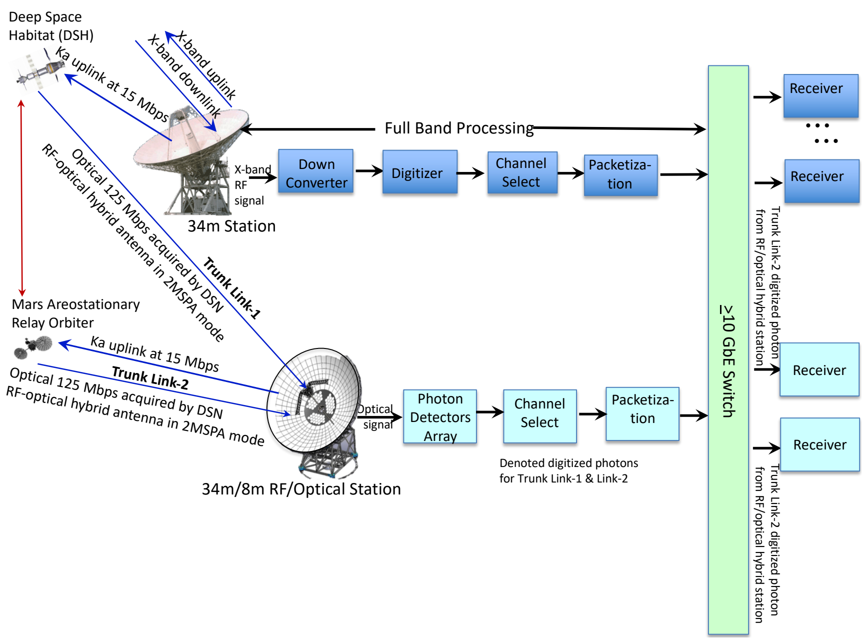

Figure 9. Mars Relay Dual-Trunk Link with Earth: Optical Option

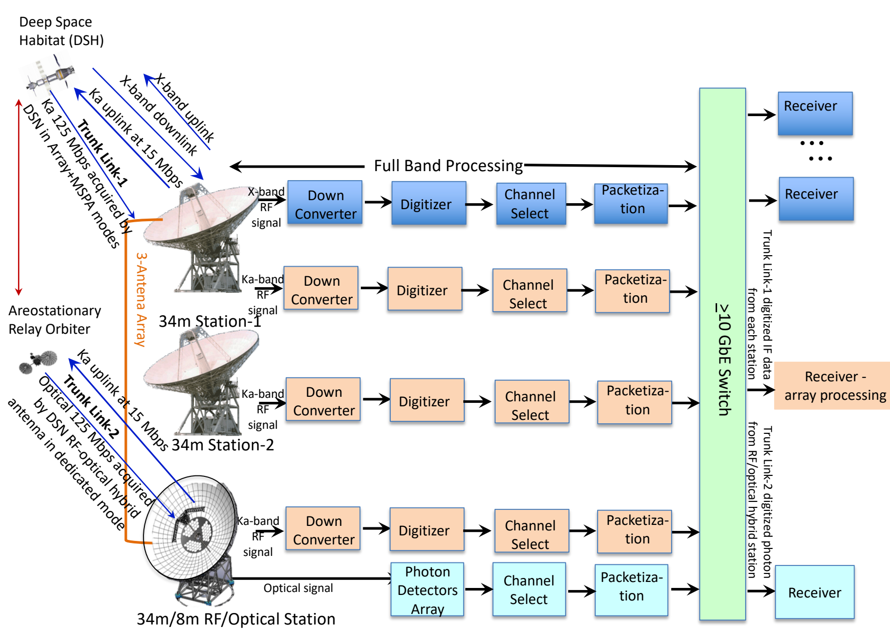

Figure 10. Mars Relay Dual-Trunk Link with Earth: Combined RF-Optical Option

Comparison of Dual-Trunk Link DSN Architecture Options

In 2015, a study, the Deep Space Optical Ground Segment Study, was conducted by JPL to assess the technical performance and cost issues for deep space optical communications. Preliminary, ROM cost estimate[13] for the various types of optical telescopes, i.e., the enclosed 12m, the enclosed 8m, and the 8m hybrid RF-optical, were generated. Using that set of cost data along with the well-known 34m antenna cost, a first-order cost comparison between the Dual Trunk-Link options and single trunk link options (both RF and optical) indicated that all three Dual Trunk-Link options would represent far more cost-effective approaches to providing the high-rate downlink/uplink capacity potentially required for the human Mars exploration era.

We were able to further conclude that, among the three Dual Trunk-Link architectures, the RF-only solution is still the lowest cost option. In addition to costs, other figures of merit (FOMs) are also considered. Table 4 provides a summary comparison of the three options.

Table 4. Comparison of Dual-Trunk Link DSN Architecture Options

	Dual-Trunk Link RF-Only	**Dual-Trunk Link Optical-Only**	**Dual-Trunk Link Combined RF-Optical**
Cost	Lowest Cost: Total for 3 DSN sites – 9 34m antennas. Scale of economy. Build to blue print. Very low NRE cost.	Intermediate Cost Total for 3 DSN sites – 3 34m antennas, 3 hybrid RF-Optical antennas. Higher NRE cost for optical due to 2-MSPA.	Highest Cost Total for 3 DSN sites – 6 34m antennas, 3 hybrid RF-Optical antennas. Lower NRE cost for optical than Optical-only.
Nominal Performance	Comparable: Capable of ~250 Mbps downlink, 30 Mbps uplink	Comparable: Capable of ~250 Mbps downlink, 30 Mbps uplink	Comparable: Capable of ~250 Mbps downlink, 30 Mbps uplink
Performance Growth Potential	a. Downlink data rates limited by total 32 GHz Ka bandwidth available to Mars mission set, 500 MHz is a hard limit. b. Uplink data rates: Significant growth space from the present use scenarios, in spite of the total 34 GHz bandwidth limitation at 500 MHz.	Total optical bandwidth available to Mars mission set is not limited, utilization of ~1.0 Gbps is not unrealistic in the future.	Total optical bandwidth available to Mars mission set is not limited, utilization of ~1.0 Gbps is not unrealistic in the future.
Performance at Mars Superior Conjunction	Design Rate: At times when the SEP angles are less than 12 degrees (e.g., superior conjunction), the system could still operate to maintain a total downlink capacity at 250 Mbps.	Degraded Rate: The system in this option is very vulnerable to superior conjunction due to its heavy dependence on optical communications. However, by shifting to an RF-only variation where both Mars relays could transmit at 32 GHz to an array consisting of the RF portion of the hybrid RF-optical antenna and the 34m antenna - all operating in a 2-MSPA mode. It would be possible to maintain a reduced	Design Rate: At times when the SEP angles are less than 12 degrees (e.g., superior conjunction), the system can readily have shifted to an RF-only variation where both Mars relays could transmit at 32 GHz to an array consisting of the RF portion of the hybrid RF-optical antenna and the two 34m antennas – all operating in a 2-MSPA mode. It would be possible to maintain a total downlink capacity that is

	Dual-Trunk Link RF-Only	Dual-Trunk Link Optical-Only	Dual-Trunk Link Combined RF-Optical
		downlink capacity at ~110 Mbps.	still very near the required 250 Mbps capacity.
Loading Reduction Potential	Lowest	Capable of off-loading high-rate RF demand by non-Mars missions.	Capable of off-loading high-rate RF demand by non-Mars missions.
Technical Maturity	Highest	Lowest (e.g., Optical MSPA)	Intermediate
Fault Resilience	Graceful Degradation: Failure or loss of any 34m antenna will result in losing only a fraction of the total 250 Mbps capacity.	Little Resilience to Ground Station Failure: a. Failure or loss of the hybrid RF-Optical antenna will result in losing the entire 250 Mbps downlink capacity. A threat to crew safety. b. Failure or loss of only the optical aperture of the hybrid RF-Optical antenna could be contained by shifting the system to an RF-only variation where both Mars relays transmit at 32 GHz Ka to an array consisting of the RF portion of the hybrid RF-optical antenna and the 34m antenna - all operating in a 2-MSPA mode. It would be possible to maintain a reduced downlink capacity at ~110 Mbps.	Multiple Graceful Degradation Options: a. Failure or loss of the hybrid RF-Optical antenna will result in reduced downlink capacity ~55 Mbps. b. Failure or loss of a 34m antenna will result in reduced downlink capacity ~180 Mbps. c. Failure or loss of only the optical aperture of the hybrid RF-Optical antenna could be contained. By shifting the system to an RF-only variation where both Mars relays transmit at 32 GHz Ka to an array consisting of the RF portion of the hybrid RF-optical antenna and the two 34m antenna - all operating in a 2-MSPA mode. It would be possible to maintain a total downlink capacity at ~250 Mbps.
Prospect of Technology Infusion	More amenable to or demanding on the following: a. 34 Ka-band uplink capability. b. 34 Ka-band uplink arraying. c. Ka-band radio metric tracking for navigation.	In addition to (a), (b) and (c) for Ka as shown in RF-only option, it is more amenable to or demanding on the following: a. 2-MSPA for optical. b. n-MSPA for optical. (Both require the cost-effective method to handle the narrow beamwidth associated with optical communications and the necessary frequency difference in the two trunk links.)	In addition to (a), (b) and (c) for Ka as shown in RF-only option, it is more amenable to or demanding on the following: c. 2-MSPA for optical. d. n-MSPA for optical. (Both require the cost-effective method to handle the narrow beamwidth associated with optical communications and the necessary frequency difference in the two trunk links.)

VI. Summary and Conclusions,

Through the Deep Space Capacity Study, we managed to define the Mars Planetary Network for human exploration era. The Mars Planetary Network would be an end-to-end system that emcompasses the Mars relay network, Mars surface network, and the Earth network. In the era of human Mars exploration, the need for resilient, persistent communication coverage for crewed vehicles, on surface and in orbits would lead to the establishment of a Mars relay network. The Mars relay network would be consisted of two areostationary Mars relay orbiters, one of them could also function as (or be served by) the Deep Space Habitat (DSH), and the relay communication payloads on the user vehicles on surface or in orbit. For the Earth network, the demands would be largely driven by the communication link over the farthest/farther Mars-Earth distance. The activity modeling and network traffic simulation/modeling we performed for the operational scenarios involving crew's activities on Mars surface have shown that the persistent, average data rate is ~250 Mbps for downlink and ~30 Mbps for uplink. At each DSN site, to meet such downlink needs, if RF-only approach is taken, three 34m BWG stations (above the currently planned) or if optical approach is taken, an optical ground telescope, with an aperture of ~8m in diameter, would have to be deployed. For the uplink, regardless of the RF or optical solution for downlink, two 34m stations would be needed at each DSN site.

The above assessment on the estimated DSN assets is contingent upon a dual-trunk link architecture in which there exists a high-rate link between the Earth station and each of the two areostationary Mars relay orbiters. Through this architecture, the required communication assets for human Mars exploration era would be reduced significantly, i.e., up to 50%, . Essential to the approach is also the existence of the crosslink between the two areostationary relay orbiters.

We have identified and evaluated three different variations of the dual trunk-link architecture for the DSN. While initial cost comparison has indicated that the RF-only option would be the lowest in development costs, we feel it is probably too soon to settle on any particular path. Advances in technology, e.g., optical communications for deep space, can significantly change which path may look most promising.

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